

IceCube : Toward a km^3 Neutrino Telescope

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Abstract—Since the end of the 2005-2006 austral summer, the IceCube detector consists of an array of 9 strings, deployed between 1450 m and 2450 m of depth and containing 540 digital optical sensors and 16 IceTop surface stations with 64 sensors. With the integrated AMANDA-II experiment this is the world's largest neutrino telescope in operation. The construction status of IceCube is presented along with an update on physics performance study for the detection of high energy neutrinos. The potential of the full km^3 -scale telescope in the search for astrophysical sources is also addressed.

I. INTRODUCTION

The first generation neutrino telescopes, such as NT200 at Lake Baikal [1] and AMANDA [2], are the proof of concept for the detection of high energy neutrinos using the Cherenkov light emitted by the charged leptons produced in charged-current interactions. Neutrino astronomy relies on the fact that these particles can propagate through the Universe undisturbed and without being deflected by magnetic fields, therefore they point back to their sources. Gamma ray astronomy is based on the same principle, but the observable distance, at TeV energy ranges, is limited to a few tens of Megaparsec due to absorption by pair production in the infrared and cosmic microwave background (see Fig. 1).

Protons can propagate deeper distances than gamma rays at a given energy, but they are deflected by the extragalactic and interstellar magnetic fields and, therefore, they cannot provide any pointing information. Only at energies above 10^{19} eV, deflection is so small that proton astronomy becomes possible. Unfortunately at those high energies proton absorption in the cosmic microwave background (GZK cutoff [3]) limits the range to a few tens of Megaparsec (see Fig. 1).

Nevertheless the detection of photons and protons with energy in excess of 10^{13} eV and 10^{20} eV, respectively, has triggered a profound theoretical dispute on the understanding of the mechanisms that produce such high energies in the Universe. Correlation of high energy gamma ray emission with the density of molecular gas in the center of the Galaxy, as detected by H.E.S.S. [4] for instance, indicates that the photons could be produced by cosmic rays accelerated in sites such as the supernova remnant Sgr A East or the black hole Sgr A*. The decay of mesons produced by proton interaction with matter and radiation, would produce high energy neutrinos as well as gamma rays. Therefore neutrino detection from the same gamma ray sources would be the definitive evidence for hadronic acceleration mechanisms in the high energy cosmic

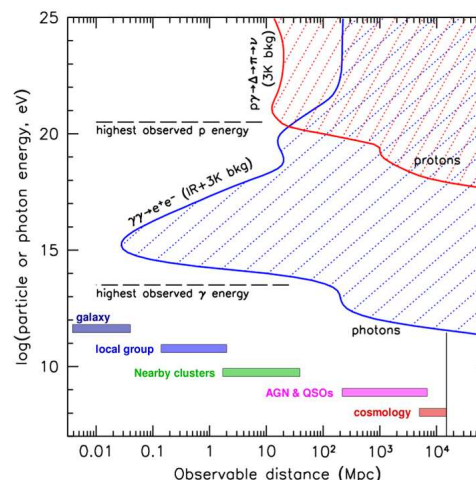


Fig. 1. Cosmic Messengers energy vs the distance within which they are detectable. Photons are affected by absorption in the infrared and cosmic microwave background : the blue shaded area represents, for any given energy, the distance range a photon cannot reach. Protons, besides undergoing deflection due to magnetic fields, are also affected by absorption in the cosmic microwave background: the red shaded area gives the distance range a proton cannot reach at a given energy.

ray sources. Similar arguments could be valid for extragalactic sources of gamma rays, even if promising sources of high energy extragalactic neutrinos could also be those with strong gamma ray absorption [5].

Unfortunately neutrinos are very difficult to detect due to their small interaction cross section, and therefore, large target volumes are necessary for their detection and identification. AMANDA has proven the feasibility of high energy neutrino astronomy and has set stringent limits on extraterrestrial neutrinos [6], [7]. Nevertheless a km^3 -scale detector is most probably the requirement for detecting expected neutrino fluxes, such as the ones from cosmic ray interactions on the microwave photons (GZK neutrinos), and for reaching the detection level of high energy neutrinos associated to the measured cosmic rays at 10^{18} eV in the hypothesis of optically thin extra-galactic sources (Waxman-Bahcall bound [8]).

The mass composition of cosmic rays is expected to become heavier at the so-called knee of the cosmic ray energy spectrum, at about 10^{15} eV. The measurement of cosmic ray energy and mass composition with good resolution can be done by detecting the correlation between the electron component at the surface and penetrating muon content (see Sec IV-B). The

South Pole location, at an altitude of about 2,800 meters a.s.l., is also characterized by reduced fluctuations in atmospheric shower size, providing better correlation to primary cosmic ray properties.

In this paper we describe the present construction status of the IceCube neutrino telescope and of the integrated surface array IceTop, as well as their verification and commissioning in view of the incoming physics results.

II. ICECUBE: DESIGN AND CONSTRUCTION

The analog technology used in AMANDA, where the signals recorded by the photomultiplier tubes (PMT) are propagated through the cables to the surface data acquisition, results to be unsuitable for a detector with a large number of sensors. A km^3 array requires semi-autonomous self-calibrating optical sensors. The digital transmission of PMT signals guarantees no data loss and allows higher dynamic range [9]. A Digital Optical Module (DOM) is the basic detection component. It hosts a 10-inch Hamamatsu photomultiplier tube and its own data acquisition circuitry, making it an autonomous data collection unit. The PMT and the data acquisition electronics are protected by a pressure-resistant glass sphere. A custom-made Analog Transient Waveform Digitizer (ATWD), samples the PMT pulse in three different gain regimes ($\times 1/4$, $\times 2$ and $\times 16$) at a rate of 300 MHz and with a depth of 128 bins (i.e. 425 ns). The same pulse is also digitized by a 40 MHz fast Analog-to-Digital Converter that records 255 samples over $6.4 \mu\text{s}$. The linear dynamic range of a DOM is 400 photo-electrons (p.e.) in 15 ns during recording phase of ATWD. The ATWD samples the pulse from any given DOM only when it has a local trigger with a neighbouring DOM. Each DOM also provides a time stamp synchronized to the surface GPS. The DOMs are also equipped with a flasher board which contains 12 LEDs that can be used to produce light pulses for calibration purposes (see Sec III).

The waveforms digitized by each IceCube string and IceTop station are sent to the surface data acquisition system, where data are time sorted. An event builder forms an event after a simple majority trigger is satisfied for IceCube and IceTop, respectively. An online filtering system at the South Pole selects only a fraction of the events to be transferred to the Northern Hemisphere through satellite for physics analyses.

The present array consists of 9 IceCube strings, deployed between 1450 m and 2450 m depth below the South Pole ice surface, with a total of 540 DOMs (60 per string). And of 32 surface tanks with 2 DOMs, each looking into transparent ice. The whole array will consist of 80 strings, for a total of 4,800 DOMs and 160 surface tanks, for a total of 320 DOMs.

The construction relies on hole drilling in the ice using an Enhanced Hot Water Drill (EHWD). The drill system consists of numerous pump and heating devices, hoses, a drill tower and a complex control. The EHWD is designed to drill holes to a depth of 2500 m in less than 40 hours, excluding the time needed for rigging. This is approximately 3 times shorter than AMANDA drilling system [10].

III. CALIBRATION

The detector calibration is one of the major efforts aimed at characterizing its response and to reduce systematic uncertainties at the physics analysis level. Each PMT is tested in order to characterize its response and to measure the voltage yielding a specific gain, currently at 10^7 in the operating detector. The gain measurement accounts for uncorrelated noise in the optical module due to thermal background in the photocathode and to radioactive decay of isotopes contaminating the glass pressure sphere. The dark noise rate is approximately 700 Hz when DOMs are in ice.

Each DOM has a free running 20 MHz oscillator which is synchronized to the surface master GPS clock every 3 seconds. A pulse with known characteristics is sent from the surface to each DOM which in turn, after synchronizing its local oscillator, sends back an identical pulse after a known time delay [9]. This procedure has a resolution of less than 2 ns.

The LEDs on the flasher boards are used to measure the photo-electron transit time in the PMT for the reception of large light pulses between neighboring DOMs. This delay time is given by light travel time from the emitter to receiver, by light scattering in the ice and by the electronics signal processing. The RMS of this delay is also less than 2 ns.

Waveform sampling amplitude and time binning calibration is periodically performed in each DOM and used to extract the number of detected photo-electrons with an uncertainty of $\sim 10\%$.

IceTop tanks are calibrated using low energy cosmic muons which deposit ~ 190 MeV, producing a signal of about 240 p.e., and which provide a characteristic peak used to calibrate the surface array.

Higher level calibrations are meant to correlate the number of detected photo-electrons to the energy of physics events that trigger the detector. A complete detector response simulation is necessary for this and the ice optical properties are one of the fundamental ingredients. These properties have been measured in the past using AMANDA in-situ calibration lasers [11] and recently using a high precision dust logger [12] that measures the dust concentration in the ice as a function of depth. The concentration of dust can be used to measure the ice optical properties.

IV. PHYSICS ANALYSES

A. Backgrounds

IceCube is triggered mainly by the intense rate of muons generated by the impact of primary cosmic rays in the atmosphere and by a tiny proportion (i.e. five orders of magnitude smaller) of atmospheric neutrino-induced events. Atmospheric neutrinos represent the irreducible background for extraterrestrial high energy neutrino searches and, therefore, it is important to understand the theoretical uncertainties derived from predictions, as well as experimental systematics, since they might affect the estimation of the sensitivity for cosmic neutrinos.

Since we use the Earth to discriminate neutrinos from downward cosmic muons, only up-going muon tracks are selected to

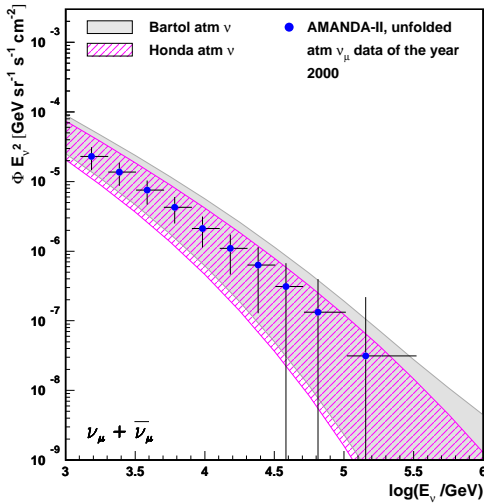


Fig. 2. Preliminary unfolded energy spectrum of atmospheric muon neutrinos measured by AMANDA-II using data collected between in year 2000. Error bars include statistics and the correlation between neighboring energy bins [15]. The theoretical atmospheric neutrino prediction shown are from [13] (Bartol) and from [14] (Honda). Bands are determined by the horizontal and vertical flux.

reduce the contamination of down-ward cosmic muon events. These up-going events are still contaminated by less than 1% wrongly reconstructed cosmic muons, which is too large. Quality cuts are designed to reduce this contamination. About a 10^6 background rejection power needs to be achieved, while maintaining the highest possible neutrino selection efficiency.

Fig. 2 shows the preliminary energy spectrum of atmospheric neutrinos measured with AMANDA-II using data recorded during in year 2000. A regularized unfolding technique has been used and bin-to-bin correlation accounted in the error bars [15]. The unfolded energy spectrum is consistent with present-day uncertainties from cosmic ray spectrum and composition, hadronic interaction models and detector response modelling.

A preliminary study of atmospheric neutrino selection has been done with the first 9 strings of IceCube using data collected and filtered online in 2006, demonstrating the stability during data taking, the reliability of the online event filtering and the mature stage of analysis tools. The final sample has been selected to have high quality events and no more than 5% cosmic muon background contamination, according to simulation.

The preliminary event selection has provided 156 observed up-going muons in 90 days livetime (starting from June 3rd, 2006). This number is consistent with the predicted $144.3 \pm 11.7_{\text{stat}} \pm 47.7_{\text{syst}}$ according to Monte Carlo simulation, of which 137.6 from atmospheric neutrinos, 4.4 from single cosmic muon events and 2.3 from double-unrelated cosmic muon events that hit the detector within trigger time window. The preliminary systematic uncertainty includes contributions from detector simulation approximations, cosmic ray flux and composition, hadronic interaction models and high energy neu-

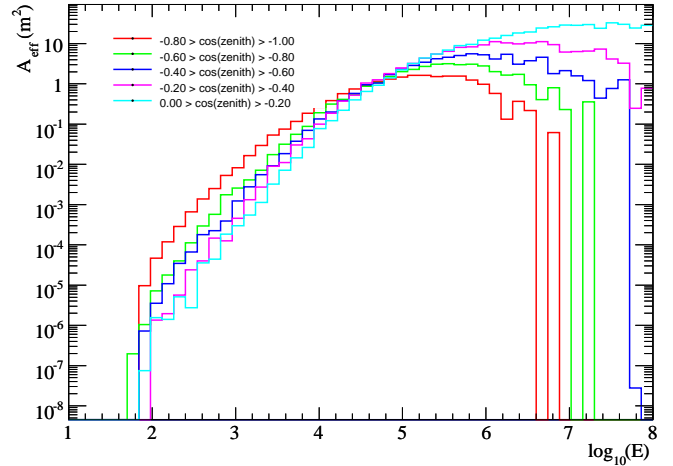


Fig. 3. Preliminary neutrino Effective Area, as a function of neutrino energy (in GeV), for selecting atmospheric neutrinos using data collected in the year 2006 by the 9 strings of IceCube. The different histograms corresponds to different angular ranges.

trino cross section. The neutrino effective area as a function of neutrino energy (see Fig. 3) is the true assessment of detector performance for the detection of neutrinos. It contains the neutrino interaction probability, muon propagation, detector response and event selection.

Fig. 4 shows the neutrino effective area as a function of the neutrino energy (top figure) for the event selection used in [26]. The acceptance for 9 strings of IceCube is comparable with AMANDA-II, and the full IceCube array is expected to increase it by more than one order of magnitude. This increase corresponds to about a factor of four better angular resolution at high energy (bottom figure). The energy range of the selected events is about 0.1-5 TeV for atmospheric neutrinos and 1-100 TeV for E^{-2} spectrum.

B. Cosmic Rays

Atmospheric neutrinos above $\sim 10^5$ GeV are produced by cosmic rays of energies greater than $\sim 2 - 10 \times 10^5$ GeV, i.e. around the knee [16]. The search for high energy neutrinos from unresolved sources (see IV-D) relies on measuring the excess of neutrinos at high energy with respect to the atmospheric irreducible background. Since the cosmic ray flux and composition have big uncertainties at and above the knee this is an important component of systematic uncertainties for the high energy neutrino measurement. The knee is believed to be caused by the escape of lighter mass cosmic rays from the Galaxy. Due to mass-dependent rigidity cutoff it is expected that the mass composition would become heavier above the knee. Experimental results, such as the AMANDA/Spase measurement [18], seem to confirm this trend. Nevertheless these results seem to be affected by systematic uncertainties that make interpretation complicated.

An efficient way to probe the primary composition is the correlation of muon to electron content in a shower. The coincident measurement of shower size and muons at the surface provides a better mass resolution (see Fig 5 on the

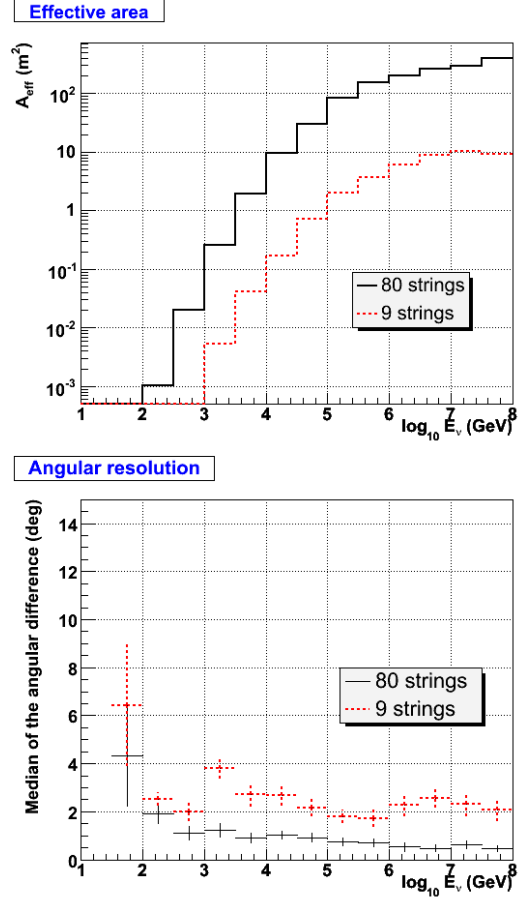


Fig. 4. Preliminary study of diffuse muon neutrino effective area and muon track angular resolution for IceCube in the present configuration with 9 strings and with the full size. Event selection is the same as from [26].

left), whereas high energy muons provide a better primary energy resolution (see Fig 5 on the right) [17].

The IceTop surface array has been designed to measure the cosmic ray flux and composition in the range $\sim 10^5 - 10^9$ GeV. The digitized waveform from the optical sensors provides an extra degree of freedom to improve the shower core reconstruction. The estimated acceptance for the present day array geometry is $\sim 0.001 \text{ km}^2 \text{ sr}$, and it will be $\sim 0.2 \text{ km}^2 \text{ sr}$ for the full array.

C. Neutrinos from Point Sources

The search for high energy muon neutrinos from point sources has been performed with AMANDA with different data sets [20]–[22]. Each of these searches did not reveal any signal, nevertheless the sensitivity has been significantly improved in time due to geometry size increase, data accumulation, better understanding of detector performance and to more efficient analysis techniques [23]. Data collected by AMANDA in the years 2000-04 have been cumulatively analysed, for a total livetime of 1001 days. This analysis, similarly to the previous ones, has filtered and selected up-going muons in order to achieve a good background rejection with

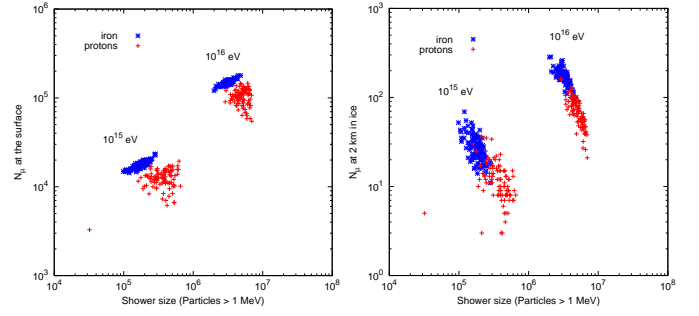


Fig. 5. Correlation between shower size at the surface and muons. Left figure is for muons at the surface. Right figure is for muons that reach 2 km depth in the ice ($E_\mu \geq 400 \text{ GeV}$). From [19]

high retention acceptance for neutrino events, combined with directional resolution optimization. The 4282 observed up-going events result to be compatible with the predicted 3627 to 4912 atmospheric neutrino-induced events from a full Monte Carlo simulation. The spread of predicted events accounts for theoretical and experimental systematic uncertainties [24], [25].

The search for point sources has been done using this final up-going muon sample with different methods. For each of them the expected background has been found using experimental data off-source from the same declination band.

A full-sky search has been performed with a binned method and the 90% CL sensitivity for a hypothetical E^{-2} flux, has been determined to be fairly constant in declination and is about $E^2 \cdot \Phi < 10^{-7} \text{ GeV cm}^{-2} \text{ s}^{-1}$ (see Fig. 6). The highest significance observed is 3.7σ and, using scrambled random sky-maps, the probability of seeing something this significant or higher has been found to be 69%.

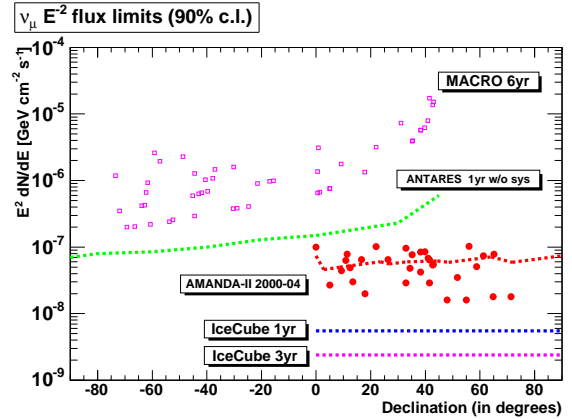


Fig. 6. Upper limits on $E^{-2} \nu_\mu$ fluxes (90% CL) vs declination using the AMANDA data collected in 2000-04 (corresponding to 1001 days livetime) for selected sources (full red circles) and sensitivity (red dashed line) [25]. The IceCube estimated sensitivity for 1 year is the blue dashed line and for 3 years in the purple dashed line [26]. The MACRO upper limits (open squares) are from [27] and the ANTARES preliminary sensitivity for 1 year is from [28].

Searches for a set of selected candidates have been also performed, as well as for stacked Active Galactic Nuclei

(AGN) candidates catalogued in different classes [29]. In each case no signal was detected and limits have been calculated for the candidate sources (see Fig 6), and for the stacked search limits are about 2-10 better than the one from full sky search.

Specific point source searches have been optimized using correlations with transient phenomena observed in different electromagnetic wavelengths. Searches of high energy neutrinos in coincidence with Gamma Ray Bursts (GRB) have also been done [30], providing no signal with an excellent acceptance, due to the good background rejection. Also for a source above the horizon, the Soft Gamma Ray Repeater SGR 1806-20, a search for muon and neutrinos from gamma ray interaction in the atmosphere has been done [31].

The expected sensitivity for the full IceCube neutrino telescope and for one year is expected to be at least one order of magnitude better than present 5-year AMANDA sensitivity (see Fig. 6). This makes IceCube suitable for probing the most promising galactic and extragalactic source candidates for neutrino emission, especially if combined in a multi-messenger search campaign, which is under development.

D. Neutrinos from Diffuse Sources

If individual point sources of neutrinos are too weak even for a km^3 -scale telescope, other techniques need to be considered to search for high energy extraterrestrial neutrinos, besides time correlation with external triggers (for GRBs) and stacking classes of AGNs. We can assume that neutrinos have been emitted by a large number of unresolved sources at all cosmological times. In this case we might look for a diffuse flux of neutrinos with no space and time correlation. Under the hypothesis that high energy neutrinos are produced by cosmic ray through second order Fermi acceleration mechanism, we expect them to have a spectrum like E^{-2} , therefore harder than atmospheric neutrinos ($\propto E^{-3.7}$). The excess of extraterrestrial neutrinos, with respect to the bulk of detected up-going muon candidates, is expected to occur in the high energy tail. AMANDA has been done diffuse searches for muon neutrinos and all flavor neutrinos.

The muon neutrino search basically selects a sample of up-going muon tracks compatible with atmospheric neutrinos, by requesting simply the event to be good quality with good angular resolution. A muon energy estimator is used to look for the optimum energy cut for selecting E^{-2} neutrinos among the atmospheric ones. Since there is no off-source background in a diffuse search, Monte Carlo simulated atmospheric and cosmic neutrinos, with event propagation and detector response, have been used for the energy cut optimization [35]. Fig. 7 shows the measured upper limits on E^{-2} fluxes. Upper limits have been calculated also for neutrino energy spectra other than E^{-2} and the results are being reported in [32].

The all-flavor neutrino search selects cascade events in the detector, rather than tracks, and thus it is sensitive to both charged and neutral current interactions. Searches of contained and semi-contained cascade events provide a good vertex and energy resolution [36], while searches of non-contained Ultra

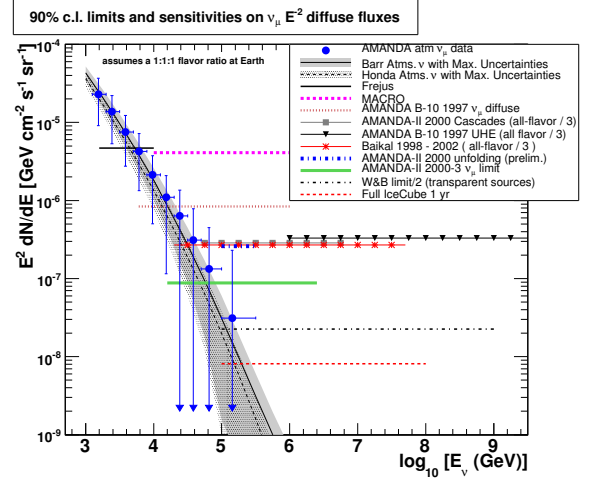


Fig. 7. Flux upper limits for diffuse neutrinos with an E^{-2} energy spectrum. All-flavor neutrino results are shown along with muon neutrino ones by dividing them by three based on the assumption of a 1:1:1 flavor ratio at Earth. This figure shows the unfolded energy spectrum of muon neutrinos from 2000 AMANDA-II [15], and the muon neutrino limits from Frejus [33], MACRO [34] and AMANDA-B10 [35]. Also all-flavor neutrino limits from AMANDA-II 2000 [36], AMANDA-B10 UHE selection [37] and the Baikal 5 year limit [38]. The Waxman-Bahcall upper bound [8] and predicted full IceCube sensitivity [9] are also shown.

High Energy (UHE) events provided extended AMANDA sensitivity up to $\sim 10^9$ GeV [37].

The IceCube neutrino telescope will significantly improve the sensitivity for detecting diffuse high energy neutrinos, as shown in Fig. 7, where it appears that Waxman-Bahcall upper bound is in the reach of IceCube.

V. PARTICLE PHYSICS WITH ICECUBE

The possibility to detect a ν_τ with a neutrino telescope is intriguing since they are expected to reach the detector in number comparable to ν_e and ν_μ as a consequence of flavor oscillation between their source and the Earth. In general the flavor ratio of astrophysical neutrinos is expected to be $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, but this ratio might easily be modified by phenomena such as neutron decay, two-photon annihilation to muon pairs or muon synchrotron cooling inside the source (see [39] and references therein).

The measurement of flux of the different neutrino flavors would open a window toward the understanding of particle physics involved in the neutrino source processes and propagation.

The experimental identification of a neutrino flavor requires a unique signature that can be discriminated from the background. The identification of ν_τ has a clear signature in a neutrino telescope when it undergoes a charged current interaction, and the produced tau lepton propagates for a given distance before decaying to produce a second cascade inside the detector. These *double bang* events are experimentally detectable in a very narrow energy range, namely $\sim 10^6$ - 10^8 GeV, and require a large volume to be able to reconstruct their unique topology.

IceCube is probing different approaches to increase the sensitivity for detection of ν_τ , such as the full use of the recorded waveform, through the recognition of the two close cascades. The τ loses energy at a higher rate than a muon with the same energy. Therefore investigations are ongoing to understand whether a tau decaying into a muon can be identified in IceCube.

VI. CONCLUSION

The IceCube neutrino telescope has been designed to be a self-calibrating apparatus where each optical sensor is a stand-alone computer requiring small maintenance while providing high performance for a long operation time. The high dynamic range of the DOMs, their detailed individual characterization and calibration, low dark noise rate and good timing resolution, make IceCube suitable for high energy neutrino astronomy. IceCube is expected to significantly improve the sensitivities achieved by AMANDA, due to its size and the use of full digitized waveforms recorded by the PMTs. Multimessenger campaigns are among the main achievements that IceCube is seeking to obtain. The surface array IceTop is designed to extend the measurement of cosmic ray spectrum and composition up to 10^9 GeV, providing an excellent primary energy resolution via coincident measurement of penetrating muons and shower size at the surface. Finally, starting from 2007, AMANDA becomes an integrated instrument within the same IceCube Data Acquisition System. The Transient Waveform Records (TWR), i.e. the digitization at the surface of the PMT pulses recorded by the denser instrumented AMANDA, will provide a good sensitivity at low energy, not reachable by IceCube only.

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